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Towards the Analysis of Reliability Index of Steel Frame Equipped with TADAS Yield Damper

Parviz Hosseini Sarjou

Abstract: During an earthquake, a considerable amount of kinetic energy from the ground acts as a lateral force on the structure, and this energy causes damage to the main components of the structure, including beams, columns and joints. To reduce the effects of earthquakes on the structure, one of the best methods is dissipation of the energy applied. For this purpose, there are various methods, one of the most practical of which is dampers. Dampers are attachments to a structure that dissipate energy and reduce damage to structural components. The present study examined the TADAS yield damper (Triangular Added Damping and Stiffness) and reliability of the structure equipped with this type of damper (particularly the reliability index) considering the uncertainty in ground motion (ground acceleration) and duration of earthquake. To achieve the objectives of the study, reliability index of the structure was calculated and compared in two modes, steel frame with damper and steel frame without damper, based on criterion of failure and drift and base shear. The results show that dampers dissipate energy from the earthquake and improve reliability and, consequently, reduce failure risk.

Keywords: energy dissipation; failure criterion; reliability; TADAS damper

1 INTRODUCTION

One of the most effective methods in analysis, decision making for component selection and structural design is application of probabilistic methods. Reliability of structures is a special method of applying probabilistic methods in structures [1]. There are two main methods for analyzing the reliability of structures, which include: 1) theoretical analysis of structural reliability, including first-order reliability method (FORM) and second-order reliability method (SORM); 2) simulation-based methods, the well-known method being the Monte Carlo simulation, which is more used in complex problems with many random variables [2]. The present study used FORM to obtain the reliability index (β).

The present study first introduced types of yield dampers and characteristics of each and how to model them, and then the FORM method was explained. Finally, three-span and five-story frames with chevron braces were modeled in two modes, with dampers and without dampers, as well as bending frames by software Sap2000. The structure response (roof displacement and base shear) were extracted and discussed by time history analysis in two types of structures subjected to different earthquake accelerations. Using the results obtained from Sap, risk analysis was performed and compared in terms of reliability index.

2 ADAS (ADDED DAMPING AND STIFFNESS) YIELD DAMPERS

Yield dampers are metal devices that can dissipate energy in an earthquake by inelastic changes in metals. These dampers actually yield in flexural, torsional, axial, or shear modes. The first idea of using yield dampers for strength of structures during earthquakes was started by theoretical work of Kelly et al. [3]. ADAS yield dampers are a special type of yield dampers that are described below.

ADAS yield dampers are inactive deformation-dependent energy dissipation systems. These types of dampers consist of X-shaped or triangular iron plates that are placed parallel to each other in the required amount. The damper made of parallel X-shaped plates is usually called XADAS and the triangular type is called TADAS. These dampers are placed in the frame at the end of the chevron braces, so that story drift causes downward movement of the upper part of the device [4]. Usually during an earthquake, when horizontal story drift occurs, a large amount of seismic energy is dissipated due to hysteresis behavior of these dampers. Figs. 1 ÷ 4 show the images of this damper [5].

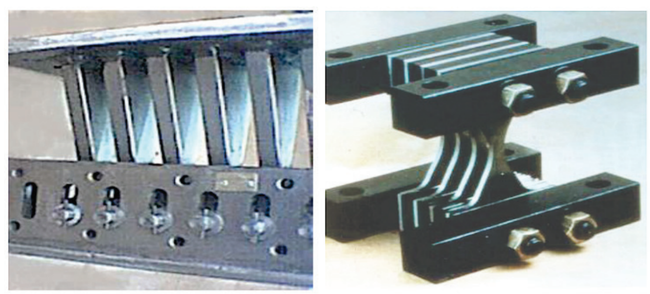

Figure 1 TADAS and XADAS dampers

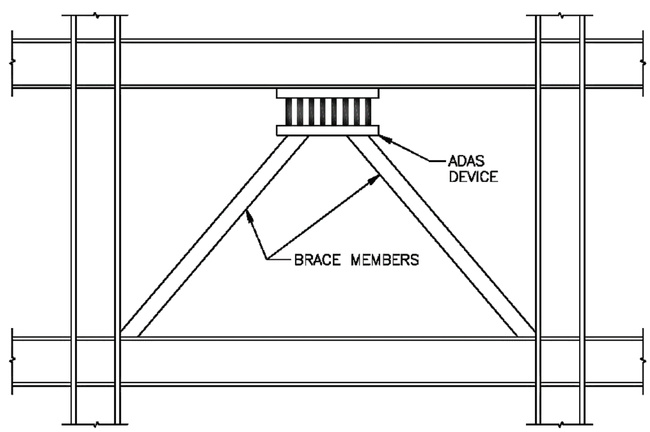

Figure 2 Position of ADAS damper in the frame

These dampers are based on yield of materials and deformation of steel plates, because a large part of input energy is dissipated in the form of thermal energy due to yield of steel plates. In other words, because of the damper shape, the metal flows when loading, which is done by placing rigid borders in the device so that the damper starts to deform with relative movement in the rigid plates up and down. Seismic experiments on a vibrating table for a 3-story model have shown that attaching the damper to the frame first increases the stiffness and second increases the energy absorption and energy dissipation of the system. For this reason, these dampers are known as added damping and stiffness [6].

Advantages of these components include [6]:

1) Large inelastic deformations are concentrated in ADAS members because these components are designed for this purpose.
2) ADAS dampers can be used in new structures as well as in old and built structures.
3) ADAS dampers explicitly increase viscous damping in structures, thus reducing the structural response to vibration and also reducing the need for dissipation in other structural members.
4) The damper is easily replaced after each severe earthquake.
5) Unlike active control dissipating systems, ADAS energy dissipation system does not require maintenance [7].

Xia [6] studied the effect of various parameters such as yield strength of the part, yield drift, as well as distribution of dampers in the building on the damper behavior. In the studies conducted, three 10-story bending frames with different ADAS elements were examined. The following results were obtained by analyzing these frames.

1) The sliding force of the damper must be large enough to dissipate more energy.
2) Yield drift of the damper should be between 0.0014 and 0.002 of the building floor height.
3) The yield strengths of ADAS components can be considered relative to the design shear forces, and stiffness of its elements can be distributed based on stiffness of the stories in frames without dampers.

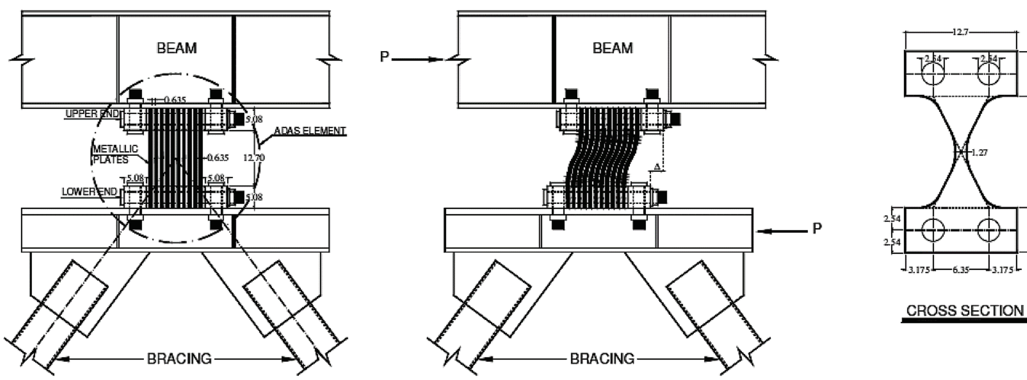

Figure 3 The shape of XADAS damper and its drift by force

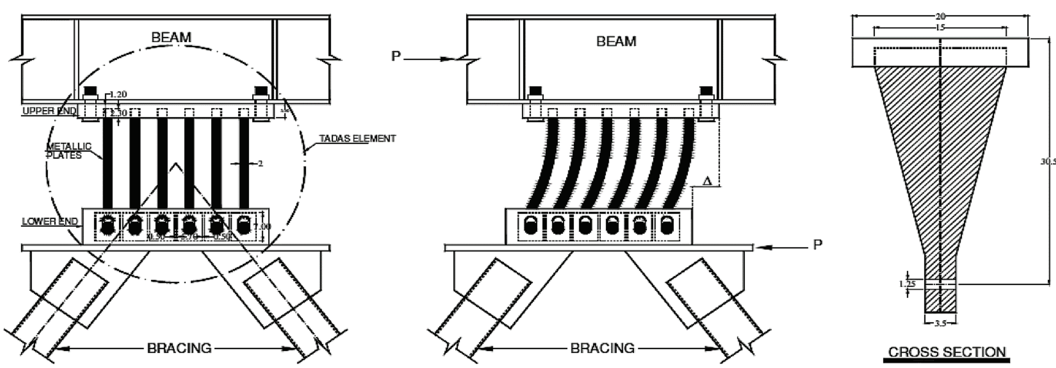

Figure 4 The shape of TADAS damper and its drift by force

Japan and New Zealand pioneered the use of ADAS damping system, but recently this technology has been used in other countries such as the United States, Mexico and India [8].

In 1990, ADAS damper was used in the building of the Heart Clinic in Mexico City. The building has 6 stories and concrete frames. By modeling this structure by Drain and analyzing the frames, it was found that application of ADAS dampers reduces the structural response to earthquakes significantly [6].

Between two types of dampers, present study examines the reliability of TADAS dampers.

3 TRIANGULAR PLATE DAMPERS (TADAS)

Triangular plate dampers are a type of yield dampers, known as TADAS (Fig. 5) [9]. Tsai (1993) studied this type of damper. He first subjected the frames equipped with TADAS dampers to cycle loading; he also considered triangular plates with different dimensions. By obtaining the most suitable dimensions for TADAS component, he dynamically analyzed a two-story steel frame using Electro earthquake accelerograms. The results of these studies showed that a significant reduction in roof displacement occurs with these dampers [6].

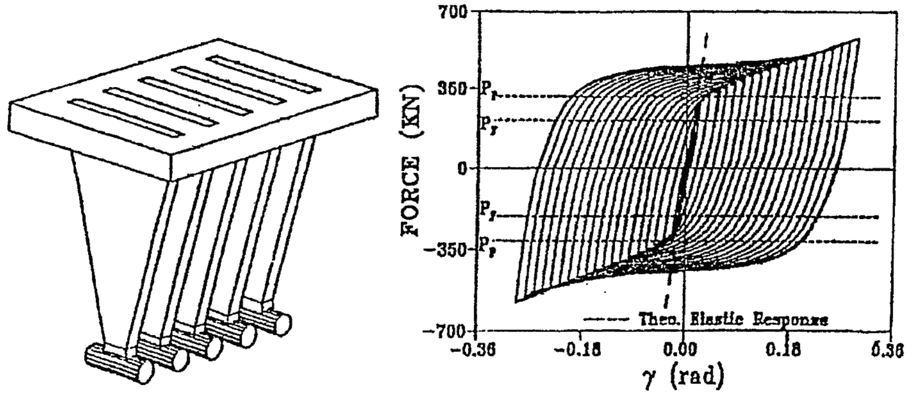

Figure 5 TADAS damper and its hysterical behavior

4 TADAS DAMPER MODELLING

Plastic Wen NLlink is used to model the metal damper by Sap software, since the damper behaves similarly to a full elastoplastic element. In order to introduce parameters of the considered element, the damper specifications introduced by Tsi et al. (1993) were used [10], as shown in Tab. 1.

Table 1 Specifications of TADAS damper in cm and kg

K_{damper}	P_y	Δ_y	*Gap* (Distance from hole to vertex)	*t* (Plate thickness)	*b* (Plate base width)	*h* (Plate height)
1802	988	0.548	1.3	2	15	30.5

For other parameters, the specification presented by Xia et al. (1992) was used [11]. For this purpose, B/D = 3, SR = 3 were used; thus [12]:

$$\frac{B}{D}=\frac{K_b}{K_d} \tag{1}$$

Where, K_b is relative stiffness of braces, K_d is elastic stiffness of TADAS damper. K_d value is calculated by:

$$K_d=\frac{P_y}{\Delta_y} \tag{2}$$

Where, P_y is yield force and Δ_y is damper yield limit drift.

Value of lateral stiffness of the damping system (damping and bracing) is obtained from the following equation.

$$K_a=\frac{K_b \cdot K_d}{K_b+K_d}=\frac{K_d}{1+\frac{1}{\frac{B}{D}}} \tag{3}$$

Where, SR coefficient is the ratio of lateral stiffness of ADAS system to building story stiffness without damping element (K_f).

$$SR=\frac{K_a}{K_f} \tag{4}$$

5 MATHEMATICAL DEFINITION OF RELIABILITY

Reliability of a system is calculated by calculating the probability of its failure according to the performance function defined by the following integral.

$$P(f)=\int_{g(x)\le 0} f(x)\mathrm{d}x \tag{5}$$

Where, $P(f)$ is probability of failure, x is the vector containing the problem variables, $f(x)$ is probability density function with problem probability variables, and $g(x)$ is system performance function. The above integrals can only be calculated by analytical methods for simple systems with low probability variables [13]. There are many methods for calculating reliability other than direct integral solution; the first-order reliability method (FORM) is one of these methods, which is known as classical first-order method. Fig. 6 shows the concept of failure schematically [13].

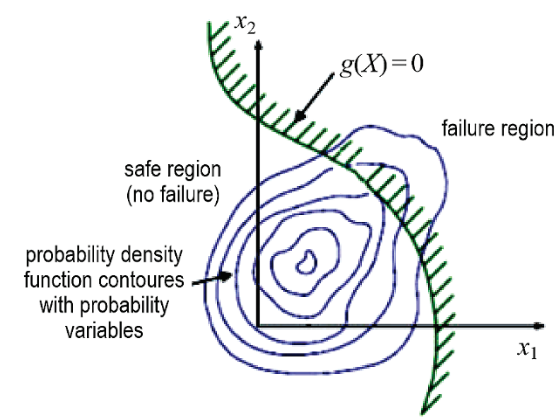

Figure 6 Schematic concept of failure

6 FIRST-ORDER RELIABILITY METHOD (FORM)

First-order reliability methods are the most common methods of estimating the level of system safety. This method is based on linear approximation of limit state function, $g(x)$, with the line tangent to the closest point of this function to origin of coordinates in the standard normal space. Determining this point requires solving an optimization problem that is done in a normal standard space.

This method involves several important steps, which are briefly described below:

Step 1: Converting the space of random variables, X, to the space of standard normal independent random variables, Z. In normal standard space, all random variables are independent of each other and the design point is much easier to calculate due to the independence of variables from each other. In other words, the shape of density with random variables around the origin is symmetric in the standard normal space, and as it moves away from the origin, its value decreases exponentially [14]. This step of the analysis is shown schematically in Fig. 7.

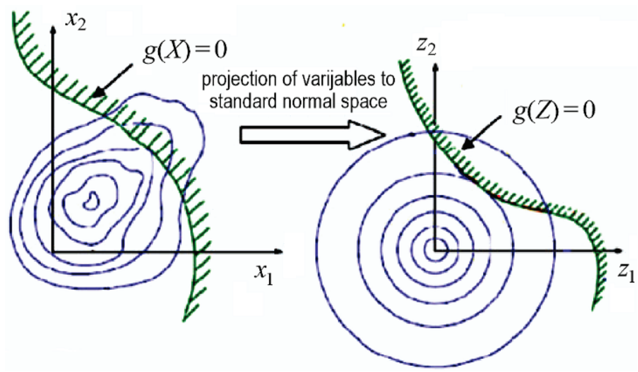

Figure 7 Converting random problem variables to normal space

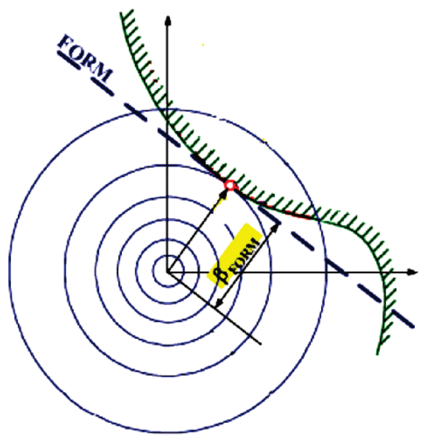

Figure 8 Approximation of F0RM method from the probability of failure

Step 2: The point with the highest probability of failure, Z, that has the shortest distance from the origin of coordinates in Z space is obtained by using suitable nonlinear optimization algorithms. This point is usually called the design point or β point, of which the distance from the origin of coordinates in the normal standard space is called the reliability index, β [14]. This step is shown in Fig. 8.

Step 3: The first-order reliability method of limit state function, $g_z(Z)$, is replaced by a first-order (linear) procedure, $g_L(Z)$, at the design point tangent to $g_z(Z)$.

Step 4: probability of failure, $P(f)$, in the first-order reliability method is obtained as follows.

$$P(f) = P\left[g_L(Z) < 0\right] = \Phi(-\beta) \tag{6}$$

Where, $P(f)$ is probability of failure and Φ is cumulative distribution function for normal standard random variable as follows:

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} exp\left(-\frac{1}{2}\alpha^2\right) \mathrm{d}\alpha \tag{7}$$

Because the objective is to compare three structural systems, it is sufficient to obtain β index for the three systems and compare them with each other.

7 MODELING SAMPLES AND EXTRACTING RESULTS

To compare two structural systems with dampers and without dampers, initially two types of bending frames and frames with dual systems (bending frame and chevron bracing) were designed by Sap2000 software; TADAS damper was then applied to the frame with dual system at the point of collision of chevron braces (as shown in Fig. 9).

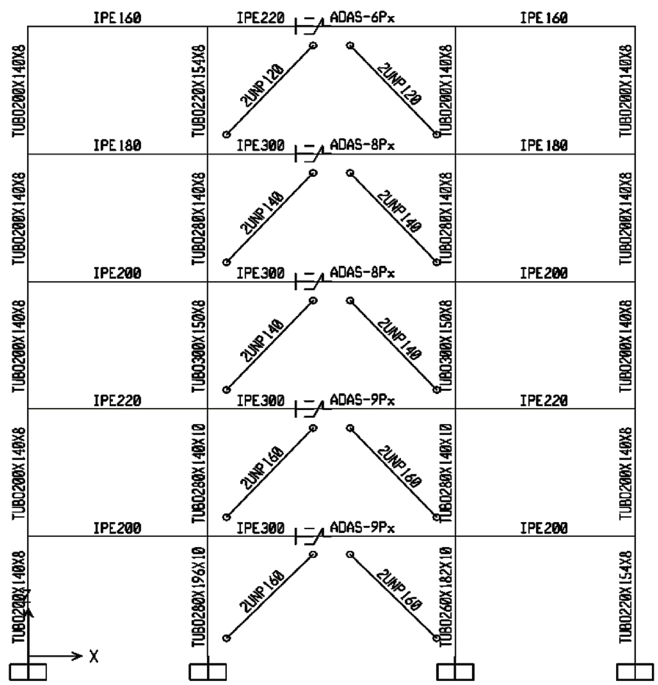

Figure 9 The frame used in the present study

Two random variables, earthquake duration and maximum earthquake acceleration (PGA), were used to model reliability. For this purpose, the models were subjected to accelerograms of important earthquakes such as Bam, Tabas, Kobe, Nordrich, San Fernando and several hypothetical accelerograms (with maximum acceleration and different duration) and structural response (last floor displacement and base shear) was extracted from the models using time history dynamic analysis. Fig. 10 shows Bam earthquake accelerogram as example.

Limit state functions are defined based on roof displacement, controlled by the allowable value, which is equal to values of the regulations. Mathematical formulation of the limit state functions was considered as follows. For the limit state based on base shear, shear value obtained in section design from static analysis of the structure was considered as allowable base shear (Tab. 2 shows probabilistic characteristics of the random variables).

$$g_1(x) = U_{\text{all}} - U_{\max} \tag{8}$$

$$g_2(x) = V_{\text{all}} - V_{\max} \tag{9}$$

Where, $U_{\max}$ is maximum roof displacement; $V_{\max}$ is maximum base shear; U_{all} is allowable drift value and V_{all} is design base shear.

Using reliability analysis, the results for limit state functions, g_1 and g_2 (Eqs. (8) and (9)), were analyzed and the results of reliability index for the two structures are shown in Tab. 3 and Fig. 11.

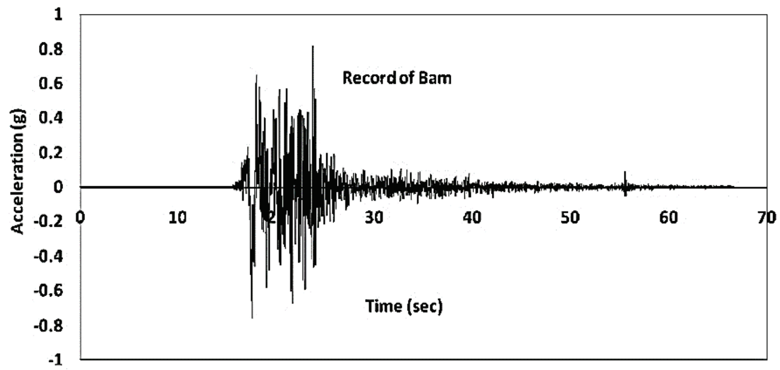

Figure 10 Bam earthquake accelerogram

Table 2 Probabilistic characteristics of random variables

Factor of variation	Mean	Probability distribution	Random variable
0.1	0.48	defined	PGA
0.1	40 s	uniform	Time

Table 3 Reliability index values (β) for three structures

	Rigid frame	Rigid + chevron	Frame with TADAS
Based on last story displacement	4.353	6.081	8.243
Based on base shear	5.245	8.561	9.21

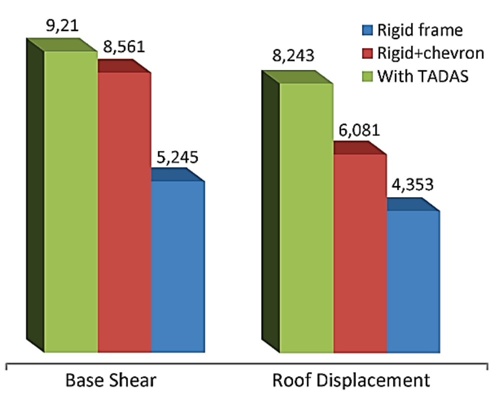

Figure 11 Reliability index values (β) for two types of systems for failure criteria based on roof displacement and base shear

Tab. 3 and Fig. 11 show reliability values for the three frame types based on failure criterion of roof displacement and base shear. Among the three types of frames discussed, the frame with damper in both roof displacement and base shear has the highest value of structural reliability (based on 9.21 base shear and 8.2242 roof displacement). The lowest values of reliability are related to the bending frame (based on 5.245 base shear and 4.353 roof displacement). The braced bending frame has values between the two previous states (based on 8.561 base shear and 6.081 roof displacement).

In general, comparison of three types of frames shows that the damper frame has the best performance and has high reliability, and values of its reliability are very different, especially from values of the bending frame. Despite the fact that the second frame uses two types of bending frame and bracing systems together, its reliability is still lower than the damping frame.

According to Fig. 11, values of reliability based on base shear are higher than the values based on roof displacement in all three types of frames. Therefore, it is reasonable to use floor displacement as a design criterion in order to design with more confidence, so that the design is done based on critical values.

8 CONCLUSION

According to the above, the following results can be extracted:

TADAS metal dampers significantly reduce the values of structural response to earthquakes (in the present study: base shear and roof displacement), which results in better seismic control of the structure.

As discussed in the previous section, dampers used in worn and weak building frames as well as installation in new structures increases structural reliability and consequently, reduces the probability of structural failure and damage; thus, dampers of old structures can be used for improvement of new structures [20].

To determine reliability, different failure criteria must be considered. For structural design, the failure criterion considered should have the lowest values of reliability to design the structure based on critical values.

Many scientists including Sedaghatnezhad, H. et al. [15] in 2022, Houshmand A. [16] in 2021 and Shojaeifar et al. [17] in 2020 studied the seismic behavior of structures equipped with various flowing metal dampers and achieved important results in seismic control of structures using dampers. In the present study, following the previous studies, reliability was determined by the Monte Carlo simulation method [21], and performance of frames equipped with dampers was evaluated in terms of reliability. Consistent with previous studies, these types of frames have a very good performance in terms of reliability.

Future studies can use more random variables (such as distance and proximity to earthquake faults, ground type, different amounts of damping driving force, application of dampers in different openings and floors, etc.), as well as different failure criteria (including relative roof displacement, floor shear, buckling of columns, etc.) to determine the reliability. By increasing the random variables and failure criteria, the reliability results will be more accurate. To evaluate the reliability of structures equipped with metal dampers, determine the reliability and structural failure, other methods such as system dynamics method [18, 19, 20, 23] can be used instead of the Monte Carlo method. These methods include meta-models such as neural networks, support machines, and kriging.

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Author's contacts:

Parviz Hosseini Sarjou
Department of Civil Engineering,
Higher Educational Complex of Saravan,
Saravan, Iran
ph.sarjou@chmail.ir